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HYPERSONIC AND UNSTEADY FLOW SCIENCE ISSUES FOR EXPLOSIVELY FORMED PENETRATOR WARHEADS

Kirk Vanden
Steve Ellison
Air Force Research Laboratory
Munitions Directorate
AFRL/MNAC
Eglin AFB, FL 32542-6810

Ben Case
Computational Mechanics Branch (TEAS)
AFRL, Eglin AFB, FL 32542-6810

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6. AUTHOR(S)

Kirk Vanden
Steve Ellison
Ben Case

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Munitions Directorate
AFRL/MNAC
Eglin AFB, FL 32542-6810

Jacobs Sverdrup
Computational Mechanics Branch (TEAS)
AFRL, Eglin AFB, FL 32542-6810

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14. ABSTRACT

The technology of hypersonic projectiles is becoming mature from a metal physics perspective but there are still unsolved challenges relating to flight characteristics and aero dynamic stability. These projectiles deform under explosive loads and accelerate to hypersonic speeds in 2x10-6 seconds. In addition, these projectiles operate at sea-level conditions, a high-speed flight regime not commonly studied. The objective of this effort is to study the aerodynamics characteristics of deformable projectiles flying at hypersonic speeds and sea-level conditions. Because aerodynamic stability is critical for proper performance it is important to know what shapes should be avoided and which ones are acceptable. Since this was a short one-year IDP task the effort only focused on static body geometries, no deformable body calculations were attempted.

15. SUBJECT TERMS

Hypersonic, Plastic Flow, Explosively Formed Penetrators, Flight Mechanics

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HYPERSONIC AND UNSTEADY FLOW SCIENCE ISSUES FOR EXPLOSIVELY FORMED PENETRATOR WARHEADS

AFOSR Laboratory IDP Task

Kirk Vanden
Computational Mechanics Branch
Air Force Research Laboratory, Eglin AFB Florida

Steve Ellison
Computational Mechanics Branch
Air Force Research Laboratory, Eglin AFB Florida

Ben Case
Computational Mechanics Branch (TEAS)
Air Force Research Laboratory, Eglin AFB Florida

Abstract
The technology of hypersonic projectiles is becoming mature from a metal physics perspective but there are still unsolved challenges relating to flight characteristics and aero dynamic stability. These projectiles deform under explosive loads and accelerate to hypersonic speeds in 2x10-6 seconds. In addition, these projectiles operate at sea-level conditions, a high-speed flight regime not commonly studied. The objective of this effort is to study the aerodynamics characteristics of deformable projectiles flying at hypersonic speeds and sea-level conditions. Because aerodynamic stability is critical for proper performance it is important to know what shapes should be avoided and which ones are acceptable. Since this was a short one-year IDP task the effort only focused on static body geometries, no deformable body calculations were attempted.

The basic concept is to use an explosive charge to rapidly accelerate a metal projectile that will be able to overcome targets possessing many inches of metal protection. Figure 1 below shows a generic EFP warhead.

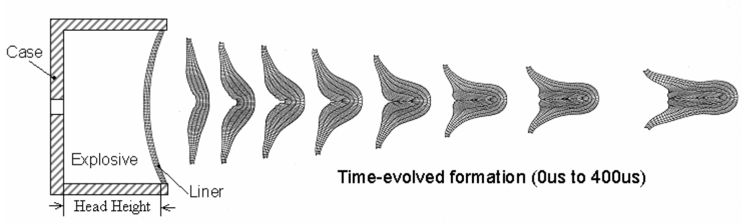


Figure 1: Generic Explosively Formed Penetrator Warhead Design

The warhead consists of a cylindrical metal case filled with explosive. One or more detonators are used to precisely detonate the explosive so that detonation waves with precise characteristics are formed. The top part of the case is open, and it is here that a metal liner is placed that will ultimately form the penetrator. Figure 1 shows not only a cross-section of the warhead, but the time evolution of the liner as it forms the penetrator.

The first area of study was to determine the level of simulation detail required to accurately model low-altitude, high-speed flow fields. This determination was made by examining the extent to which the computations are affected by atmospheric gas reactions in a high-temperature environment. Two different flow solvers were used to compute the sea-level, Mach 6 flows. These were the Beggar and Vulcan codes.

The Air Force SEEK EAGLE Office (AFSEO) Beggar code integrates an ideal gas Navier-Stokes flow solver, a 6 degree-of-freedom (6DOF) trajectory integrator, and an automatic overlapping grid system assembly algorithm into a single code. Beggar is primarily used in object motion simulations. Because of its capabilities, Beggar would seem to be the ideal choice for use in this research effort. However, Beggar has not been found to work reliably in previous attempts to compute flow field simulations at the flight conditions under consideration.

Two particular shortcomings have been identified in past high-speed applications of Beggar. First, the slope limiter functions for the upwind flux schemes are not applied to the flow properties computed on the “ghost-cell” side of the boundary faces. This can result in numerical instabilities that cause the code to fail. Second, Beggar uses an ideal gas formulation that may yield inaccurate flow property values in high-speed, low-altitude flow-field simulations. There is a temperature-dependent model for the ratio of specific heats (γ) in Beggar that could conceivably be used to alleviate the latter concern. However, this algorithm is of dubious origin and has not been actively maintained in recent years as new capabilities have been added to Beggar. For these reasons, the variable γ formulation in Beggar has been deemed untrustworthy and is not used.

This research effort was originally planned as a cooperative effort with the Air Vehicles Directorate (AFRL/VA). VA personnel were to supply a new, real-gas effects version of the AVUS (Air Vehicles Unstructured Solver) flow solver code, which MNAC personnel would apply to the EFP research. However, personnel turnover at VA resulted in development delays that meant the new code would not be available to MNAC for use in the initial stages of this project.

The NASA Langley Research Center Vulcan code was selected as an interim analysis code based on the investigator’s past assessments of hypersonic aerodynamic analysis code capabilities. Vulcan is a structured grid Navier-Stokes flow solver with integral chemical reaction modeling algorithms. Vulcan can be used to perform either steady-state or time-accurate flow field simulations involving high temperature gas effects and/or combustion.

Several sea-level, Mach 6 flow fields were computed for a 45-degree sphere-cone configuration. Given the difficulty of gridding complex EFP shapes with structured grids this idealized shape was selected to permit an easier initial analysis of the high temperature flows we expect to encounter. A baseline ideal gas solution was computed using Beggar. An ideal gas solution was computed with Vulcan so that a direct comparison could be made of solutions from the two codes. Frozen flow and reacting flow solutions were also computed using Vulcan.

A total of five flow field solutions were computed. A solution baseline was established by computing ideal gas solutions using both Beggar and Vulcan. Next, a 5-species (N_2, O_2, N, O, NO) reacting flow simulation was computed using Vulcan. This solution was examined to determine the extent of chemically reacting flow in the flow field. Because no chemically reacting flow was observed in this chemically reacting flow solution, a 2-species frozen flow simulation was run, followed by a 4-species (N2, O2, Ar, CO2) simulation, in order to assess the level of atmospheric modeling accuracy required to adequately model low hypersonic, sea-level flow fields. The input parameters for the simulations are summarized in Table 1. The simulation results are summarized in Table 2 and discussed in the following sections.

Table 1: Hypersonic Simulation Input Parameters

Mach Number	6.0
Static Density	1.225 kg/m3
Static Pressure	101325 Pa
Static Temperature	288.16 K
2-Species Simulation Mass Fractions	$f_{N2} = 0.7655$ $f_{O2} = 0.2345$
4-Species Simulation Mass Fractions	$f_{N2} = 0.7552$ $f_{O2} = 0.2314$ $f_{Ar} = 0.0129$ $f_{CO2} = 0.0005$

<u>IDEAL GAS SOLUTIONS</u> - The Beggar solution was difficult to obtain. Beggar has not proven to be very robust in past attempts to run flow solutions of this type. The solution was computed using a Steger-Warming upwind flux algorithm and the Spalart-Allmaras turbulence model using a solution time step of 10^{-6} sec.

The Vulcan solution was run more easily, primarily using the default solution parameters suggested by the Vulcan GUI. A second order Roe upwind flux scheme was employed along with two levels of grid sequencing and a steady state (local time-stepping) solution algorithm. Because the “carbuncle phenomenon” manifested in some of the low hypersonic solutions, an entropy fix was applied to the Roe scheme convection eigenvalues.

In Table 2 it is apparent there are some differences in the solutions provided by Vulcan and Beggar. Because Beggar was so difficult to run for this case, an underlying reason for the differences was not sought. However, the two solutions share an important similarity in that both solutions have maximum temperatures in excess of 2350 K, which approaches the temperature at which diatomic molecules begin to dissociate.

Table 2: Hypersonic Simulation Results Summary

Flow Parameter	Flow Parameter Range by Solution				
	Ideal Gas (Beggar)	**Ideal Gas (Vulcan)**	**5-Species Reacting Gas (Vulcan)**	**2-Species Frozen Flow (Vulcan)**	**4-Species Frozen Flow (Vulcan)**
Mach Number	0 – 6	0 – 6	0 – 6	0 – 6	0 – 6
Density	1.225 – 7.082	1.225 – 6.895	1.225 – 7.864	1.225 – 7.864	1.225 – 7.892
Pressure	1.013×10^5 – 4.752×10^6	1.013×10^5 – 4.678×10^6	1.017×10^5 – 4.736×10^6	1.017×10^5 – 4.736×10^6	1.012×10^5 – 4.710×10^6
Temperature	288.16 – 2353.2	288.16 – 2365.48	288.16 – 2091.27	288.16 – 2091.27	288.16 – 2081.27
Ratio of Specific Heats (γ)	1.4	1.4	1.294 – 1.399	1.294 – 1.399	1.294 – 1.398

CHEMICALLY REACTING FLOW SOLUTION - A 5-species (N_2, O_2, N, O, NO) chemically reacting flow solution was run with the Vulcan code using the initial mass fractions indicated in Table 1. This solution was computed to determine whether the field temperatures were sufficiently high to induce diatomic oxygen dissociation. The simulation was run using the same basic solution algorithm as the ideal gas solution, along with gas thermodynamics and chemical kinetics models supplied with the Vulcan code. A 5-reaction chemical kinetics model was used. The initial mass fractions are shown in Table 1.

No evidence of oxygen dissociation was found in the flow field. However, variation in the ratios of specific heats (γ), decreased peak temperatures, and increased density peaks in the flow field (see Table 2) are evidence of variations in molecular vibration induced by the shock.

FROZEN FLOW SOLUTIONS - A 2-species (N_2, O_2) frozen flow solution was run with the Vulcan code. This solution was run in order to determine whether the frozen flow option yielded the same results as the chemically reacting flow option with no chemical reactions occurring. As shown in Table 2, identical flow property ranges were obtained in the two solutions, indicating the frozen flow simulation does indeed duplicate the reacting flow solution.

A 4- species (N_2, O_2, Ar, C O_2) frozen flow solution was run using the initial mass fractions indicated in Table 1. This was done to determine the effect of modeling more of the atmospheric constituent gases on the solution outcome. As indicated in Table 2, adding Ar and CO_2 to the simulation had a mild effect on the results.

COMPARISON OF FLOW SOLUTIONS - The ideal gas solutions differed from each other for unknown reasons. However, both ideal gas solutions exhibited peak temperatures in excess of 2350 K, approaching the temperature at which diatomic oxygen begins to dissociate.

A 5-species reacting gas simulation computed with Vulcan showed no dissociation. However, the flow field properties in this solution were markedly different from those calculated in the ideal gas simulations due to variation in the gas thermal properties arising from direct modeling of the constituent gases. In particular, the peak temperature in this solution was approximately 275 K lower than the peak temperature in the ideal gas solution.

A 2-species frozen flow solution yielded minimum and maximum flow field properties identical to those calculated in the reacting gas simulation. A 4-species frozen flow simulation yielded mildly different results than the 2-species solution. However, the flow parameter variations are great enough to warrant including the extra gas species. For this reason all future work will be with 4-species frozen flow.

AERODYNAMIC STABILITY ANALYSIS – Once Vulcan was selected as our interim code we then began running solutions of representative EFP shapes to begin looking at aerodynamic stability and general flow phenomena. We chose a very complex shape to study first because we wished to make sure our methodology would be sufficient for even the most complex shapes we hoped to encounter. A set of analytical parameterized equations was developed to describe the shapes of the class shown in Figure 2.

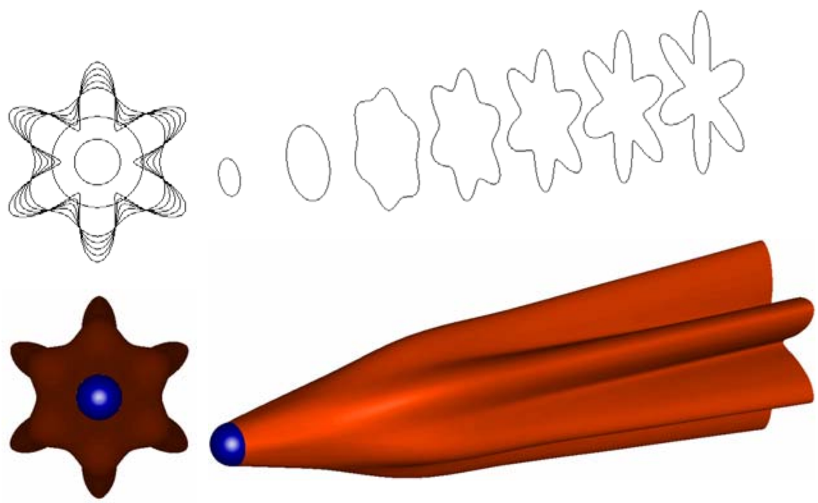
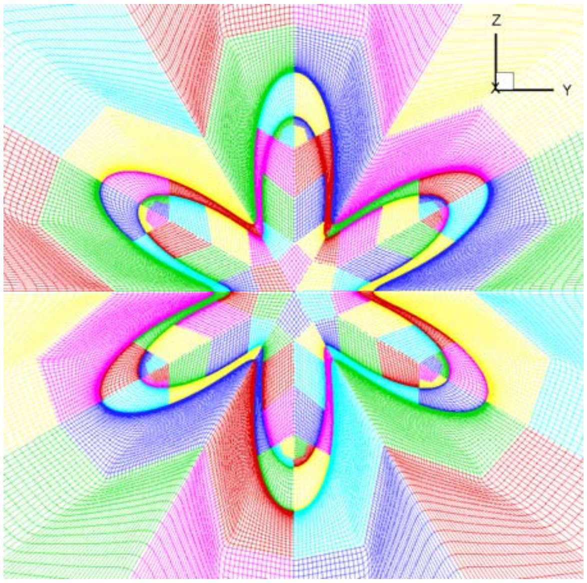


Figure 2: Generic EFP Shape

We then developed, through a very time-consuming process, acceptable structured grids. These required a very complicated grid topology. It is hoped that this manpower intensive grid work can be eliminated once we are able to obtain the AVUS code. The complex grid topology required to grid the above shape is shown in Figure 3. Note that this shape is hollow inside and the grid extends well inside the body towards the nose.



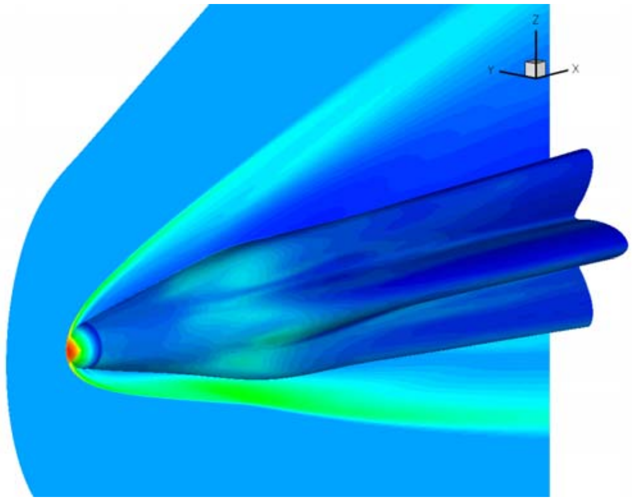


Figure 3: Grid topology at the back of the grid.   Figure 4: Flow at 5 Degrees AOA

The shape shown in figure 2 is used as a baseline and additional body shapes have been generated that have different lengths, different number of metal folds near the rear, different height metal folds, or have a different rate of transition from the rear "flower petal" shape to the circular geometry near the nose. Each of these can be varied by changing constants in the set of analytical equations developed. A parametric study can then be performed to determine which body characteristics have the most effect on aero stability as a function of angle-of-attack. This study was underway as of the writing of this project summary.

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Personnel Supported During Duration of Effort

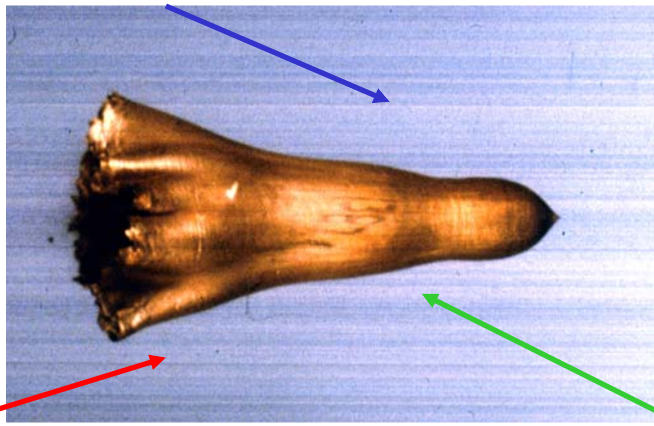
Kirk Vanden — Principle Investigator (partially supported by AFRL/MN funds)

Ben Case — Research Engineer (partially supported by AFRL/MN funds)

(Steve Ellison was supported entirely with AFRL/MNAC internal funds).

Hypersonics of Explosively Formed Projectiles
Munitions Directorate, Dr. Kirk Vanden

Sea Level Conditions



Accelerates to Hypersonic Speeds in 2×10^{-6} seconds

Body Shape Starts as a Flat Plate and Forms During Flight

Long-Term PAYOFF: Increase stable flight distance by 100% while reducing testing costs.

OBJECTIVES

- **Quantify aerodynamic loading on a non-uniform real-time deforming geometry.**
- **Understand the degree to which aerodynamic loads affect the formation of the projectile.**
- **Determine aero-stability characteristics to help guide warhead designers. Need to increase stand-off range.**

APPROACH/TECHNICAL CHALLENGES

- **Focus on understanding the hypersonic flow physics associated with explosively formed projectiles**
- **Perform calculations to study aerodynamic stability of complex shapes under going real-time dynamic deformation.**

ACCOMPLISHMENTS/RESULTS

- **Completed initial assessment of flow chemistry**
- **Completed initial stability analysis**

FUNDING ($K)—Show all funding contributing to this project

	FY06	FY07	FY08	FY09	FY10
AFOSR Funds	50				
MNAC 6.2 Funds	200	200	200	200	200

AFRL/MNAC Staff

Dr. Kirk Vanden, Mr. Steve Ellison, Mr. Ben Case, Dr. James Wilson

LABORATORY POINT OF CONTACT

Dr. Kirk Vanden, Computational Mechanics Branch (MNAC)

Numerical Experiments Performed to Determine the Level of Simulation Detail Needed to Accurately Model Low Altitude, High Speed Flows

Goal is understand what level of chemistry modeling is needed to model hypersonic flows at sea level conditions. This is critical for later analysis of aero-stability and unsteady flow issues.

Flow Parameter	Flow Parameter Range by Solution				
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Mach Number	0 – 6	0 – 6	0 – 6	0 – 6	0 – 6
Density	1.225 – 7.082	1.225 – 6.895	1.225 – 7.864	1.225 – 7.864	1.225 – 7.892
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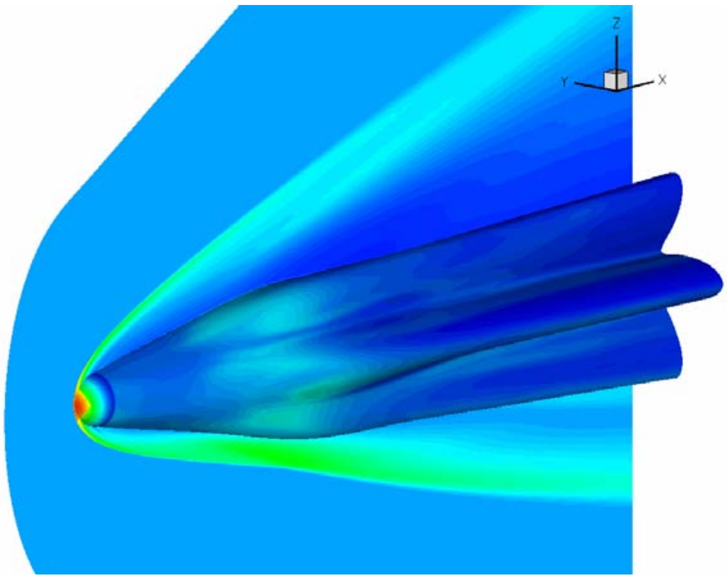

- **Ideal gas solutions had temperatures of 2350K, near the temperature diatomic oxygen begins to dissociate.**
- **A 5 species reacting gas simulation had temperatures 275K lower, and no dissociation.**
- **Frozen flow simulations with both 2-species and 4 species were calculated.**
- **It was determined that a 4-species frozen flow is an acceptable level of modeling for high-speed flows at sea-level conditions, for the current geometry.**

K. Vanden, S. Ellison, B. Case, J. Wilson / AFRL Munitions Directorate